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RECYCLED-PLASTIC JOINTS FOR EARTHQUAKE RESISTANT INFILL PANELS

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ABSTRACT

Without any exception, earthquakes in high seismic hazard areas have highlighted that preventing collapse of non-structural elements is crucial in ensuring life safety. Several studies have demonstrated that both external and internal infill panels, made from bricks and mortar joints, because of their interaction with the structural systems (usually neglected in structural modeling) are subjected to significant damage related to their in-plane resisting mechanisms. Moreover, infills are also subjected to out-of-plane forces, which may induce overturning.

In order to ensure an adequate safety level to the construction as a whole – structural and non-structural elements – it is therefore necessary to design infill walls against, both, in plane and out of plane collapse.

In this paper, the issue is coped with from a technological standpoint, by proposing an innovative constructive system for infill panels, in which the traditional masonry blocks are connected, rather than with mortar layers, through joints made from recycled plastic. They are constituted of a planar surface with a number of protruding “teeth” on both sides that fit into the holes of the blocks. The teeth allow for a certain displacement to occur at the joint level, thus reducing the in-plane stiffness of the infill panel and, as a consequence, its damage; at the same time, they realize an interlocking mechanism that prevents the out-of-plane collapse.

The study is completed by the development of a simple and effective procedure for the design of the capacity of masonry infill panels with respect to the in-plane and out-of-plane behaviors.

INTRODUCTION

The seismic events that cyclically affect earthquake-prone regions have increased the awareness of the Scientific community about the vulnerability of non-structural elements, such as infill panels and partition walls. The literature on this subject has significantly intensified so that current advanced construction codes incorporate specific requirements for checking the safety of non-structural elements, as well. Such studies have in fact shown that the infill panels subjected to in-plane action provide a significant contribution in terms of stiffness and strength (Broken and Bertero, 1981), (Fardis and Panagiotakos, 1998), thus becoming by all means elements that contribute to the resistance to horizontal actions, by working in parallel with the main structural system. When horizontal actions are applied perpendicular to the mid-plane, in most cases the infill panels show a very high vulnerability and tend to overturn (Abrams et al., 1996). If the interaction between infill masonry

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panel and the r.c. frame is not negligible, its contribution must be explicitly taken into account when modeling the structural system.

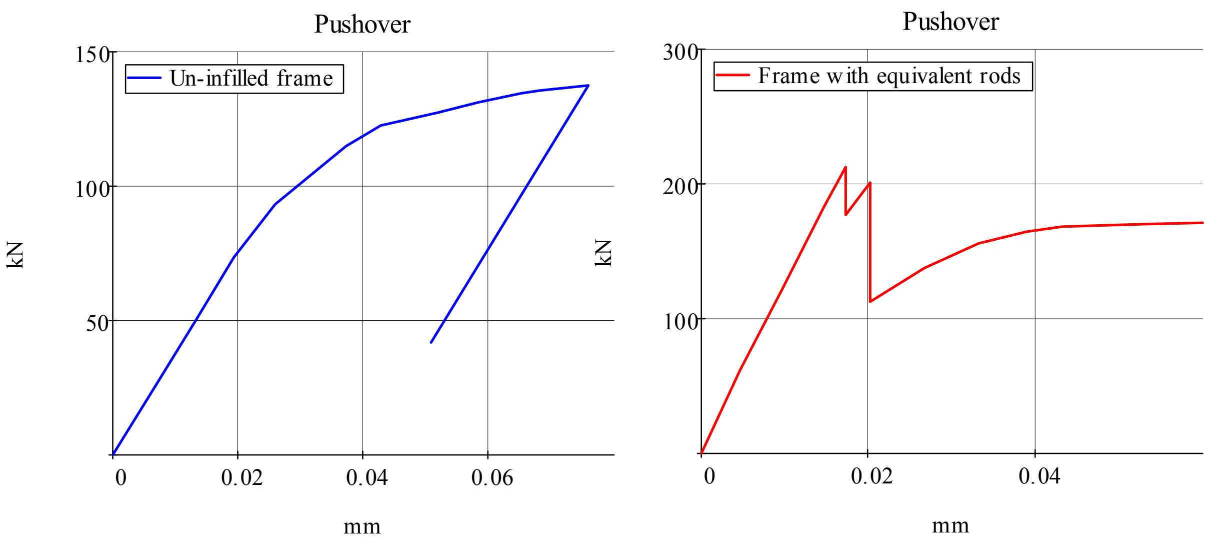

Figure 1. Example of multistory frame model. Left, without infills, right with equivalent rods to simulate the interaction framework/infills.

Numerical simulations conducted on a simple non-linear frame with concentrated plastic hinges, as shown in Fig. 1 for the sake of exemplification, show remarkable differences in the structural response with and without infills (Vailati, 2004), which can be summarized with:

- An increase in the elastic stiffness;
- A rather pronounced decrease of stiffness and strength (saw-tooth shape) before attaining the final displacement.

As seen in the capacity curve of the infilled frame in Figure 1, a brittle collapse of the column may also occur, while still elastic, due to the increase of shear produced by the horizontal component of the compression force, which develops in the inclined strut representing the infill panel; this greatly affects the displacement capacity of the structure and can trigger partial collapses dangerous for the safety of human life.

The simulations of frame/infill interaction, along with the observations of buildings damaged by earthquakes demonstrate that the infills suffer from too high an in-plane stiffness. In case of high intensity earthquakes, the demand is usually too high for traditional infills, thus giving rise to either in-plane shear collapse or partial/total outwards expulsion.

Why then not to try and solve the problem by following a completely different strategy? In other words: by pursuing flexibility rather than stiffness.

This unconventional point of view allowed for the development of an innovative construction system of infill panels and partition walls having large displacement capacity and not interacting with the surrounding r.c. frame.

FLEXIBILITY AND RESILIENCE

Throughout history, man has often drawn information from its scientific past and reformulated it into modern effective solutions for current problems.

Pertaining to this subject is an essay published in *An American Architecture* magazine (Kaufmann, 1955), by the great American architect F.L. Wright: ”We solved the problem of the menace of the quake by concluding that rigidity could not be the answer, and that flexibility and resiliency must be the answer... Why fight the quake? Why not sympathize with it and outwit it?”.

This brief reflection, 80 years old yet very modern, contains one of the founding principles of modern seismic engineering, which suggests how to effectively reduce the vulnerability of infills subject to the devastating effects of earthquakes.

The key concept of the proposed technology lies in the connection system among the infill blocks: it consists of thermoformed recycled plastic joints that are dry-assembled.

In our view, under the displacement imposed by the seismic action, we can make the wall behave as a system of essentially undeformed blocks that slide relatively to each other along the bed joints.

In this way, the mechanics of the resisting system is modified; the wall acts in fact as a series system consisting of rigid blocks, the bricks, and of flexible elastic interface springs, the plastic joints.

These horizontal joints, placed at the interface between the blocks, replace the traditional mortar bed joints. The horizontal displacement is localized at the joints, thus keeping the blocks essentially undeformed.

In a sense, the approach taken follows the line of the capacity design principle: failure of brittle elements, the bricks, is avoided by increasing the ductility of the deformable elements, the joints.

THE PLASTIC JOINTS “PLASTILINK”

The joints are made with recycled plastic and their production follows a controlled industrial process, that guarantees the stability of the physical-mechanical properties of each piece.

The joint is composed by a 300x258 mm horizontal plane with a thickness of about 2 mm, on which are extruded, in two opposite directions, some thermoformed hollow teeth that are to be inserted into the holes of the brick blocks. Fig. 2 at left shows a graphical representation of the joint.

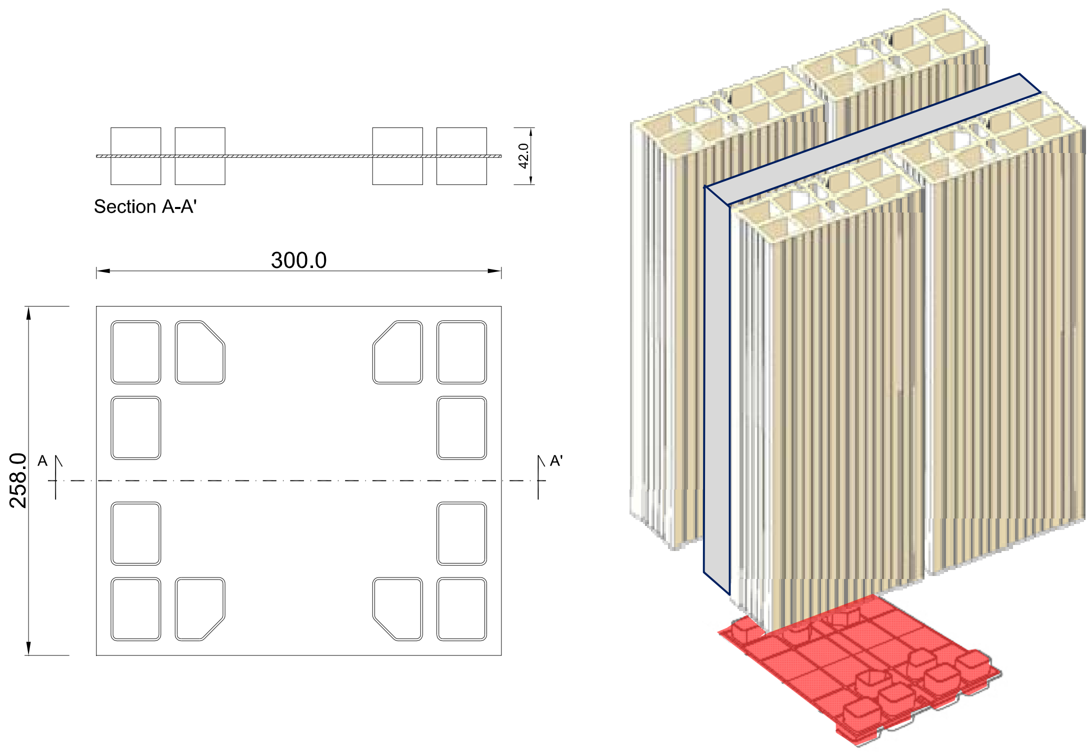

Figure 2. at left, geometric configuration of recycled plastic joints. At Right, assembled system with joint (red), bricks (light yellow), isolation layer (grey).

As mentioned before, the performance requirements are of a multidisciplinary nature. Therefore, joint size is the result of studies that aim at complying with different requirements; the double alignment of the blocks, represented in Fig. 2 at right, provides the wall with good thermal properties, thanks to the insertion of insulating elements in the air chamber between the blocks.

The joint sliding significantly reduces the horizontal stiffness of the wall, which consequently does not interact with the surrounding r.c. frame, thus preserving the dynamic properties of the system.

RECENT EXPERIMENTAL STUDIES

This technology has recently undergone an extensive program of experimental tests (Vailati et al., 2014). The study reported in great detail the results of tests performed on the material, on the joint and on full scale walls, thus showing the potential of the technology to limit the damage to infill walls, for both in-plane and out-of-plane forces.

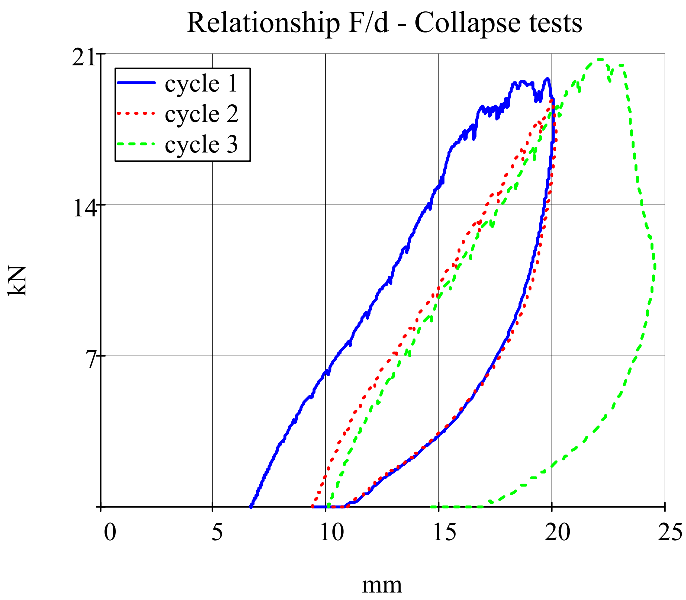

Figure 3. Cyclic behavior to collapse of joint assembled with bricks.

The tests on full scale joints and panels confirmed the remarkable sliding capacity of the infills with plastic joints, which have been subjected to much higher displacement levels than those generally experienced during seismic events.

Figure 4. Cyclic behavior to collapse of joint assembled with bricks.

Particularly effective were the tests performed on 3x3 perforated panels; for a drift of 10 cm, equivalent to 3% of the interstory distance, no constructive element of the panel, neither joint nor block, showed visible damage and remain perfectly functional. Fig. 4 shown this significant result. The out-of-plane tests provided a similar outcome.

ITALIAN CODE IN THE DESIGN OF NON-STRUCTURAL ELEMENTS

The current Italian Code NTC-08 requires that non-structural elements be verified for: Damage Limit State for the in-plane response, and Life Safety Limit State for the out-of-plane response.

In the first case, verification is performed in terms of deformation, by comparing the displacement demand, expressed by the interstory drift, with the displacement capacity, as a function of the infill-frame interaction level.

In the second case, verifications are carried out in terms of resistance, by comparing the overturning force with the corresponding capacity.

In-Plane Verification

In order for the Damage Limit State (DLS) to be verified, the interstory drift must be:

$$d_r \leq 0.01h \tag{1}$$

in which:

d_r interstory drift of the frame containing the infill;

h interstory height of the frame containing the infill.

Out-Of-Plane Verification

When verifying the out-of-plane behavior in the Life Safety Limit State, the overturning force is determined by applying a horizontal, evaluated as:

$$F_a = \frac{S_a \cdot W_a}{q_a} \tag{2}$$

in which:

F_a horizontal seismic force applied at the centroid of the non-structural element in the most unfavorable direction;

W_a weight of the element;

S_a spectral acceleration, in terms of *g*;

q_a behavior factor of the element (at most $q_a = 2$).

The spectral acceleration is evaluated as:

$$S_a = \alpha \cdot S \cdot \left[\frac{3 \cdot \left(1 + \frac{Z}{H}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - 0,5 \right] \geq \alpha \cdot S \tag{3}$$

where:

α peak Ground Acceleration, in terms of *g*;

S	coefficient accounting for soil type and topographical conditions;
T_a	fundamental period of vibration of the non-structural element;
T_1	fundamental period of vibration of the building in the considered direction;
Z	height of the overturning line of the non-structural element, measured from the foundation level;
H	height of the building, measured from the foundation level.

The demand generated on the element by the force calculated in Eq. (2) is compared with the capacity of the system.

INNOVATION AND DESIGN: A CASE STUDY

The technology of plastic joints has recently been used in the construction of the perimeter infill walls for the expansion of the Faculty of Law, within the college town of Rome.

Figure 5. Raised part of the building (red box) where the system PlastiBloc was adopted.

The portion of the building in which the infills will be created by adopting the innovative technology is constituted by a steel elevation on two levels. The image in Fig. 1 highlights the steel elevation in which the system of infills with plastic joints will be adopted.

The first interstory has a net height of the wall panel equal to 509 cm, while the second goes down to 410cm. This has required the study and development of a vertical strengthening with special plastic strips, as shown in Fig. 6, in addition to the the standard system PlastiLink, briefly mentioned previously.

The strips are designed to act as a real armature since are suitably arranged on the side of the stretched fibers, in an ideal scheme beam support at the ends, which can be connected to the wall.

The standard PlastiLink system has therefore evolved to the PlastiBloc, called as is to distinguish it from its previous patent and able to solve many aspects that emerged in this particular project.

THE SOLUTION TO A MULTIDISCIPLINARY PROBLEM: THE "PLASTIBLOC"

The PlastiLink system joined with conventional infill blocks gives rise to the so-called "PlastiBloc system", which has the following advantages:

1. Safety against horizontal forces;
2. Self-extinguishing: therefore avoids problems associated with the possible propagation of a fire;
3. The dry assembly of the plastic joints significantly reduces the infills construction time, eliminating not only the time strictly necessary for the mixing of the construction material and the realization of laying surfaces for the blocks, but also the time essential for the setting of the mortar;
4. The assembly process is also reversible and allows for repositioning of the walls;
5. Because they are made with plastic waste material, the joints can be fully recycled for the production of new artifacts, thus becoming a product with close to zero emission of CO2 (ISO/TS 14067, 2013);
6. A weight reduction between 30% and 60%, which implies lower seismic forces.

İn the following picture, the system PlastiBloc is presented. Note the strips to increase the out-of-plane capacity.

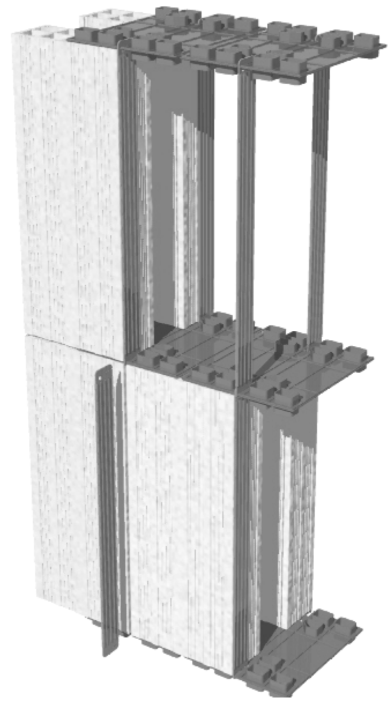

Figure 6. PlastiBloc system with vertical strengthening plastic strips.

EVALUATION OF THE CAPACITY

This work focused on the out-of-plane behavior of system Plastibloc, using two models, analytic and numerical.

The forces acting on the cross section of the wall are evaluated taking into account a distribution of the triangular tensions, resulting in compression and tension placed symmetrically with respect to the barycentric axis of the section of hollow tile, with an internal arm equal to 0.8d, where d is the thickness of the hollow tile .

The diagram in the Fig. 7 shows the reference section of the infills and the distribution of the forces adopted. Consider this diagram symmetrical with respect to an inversion of sign of the seismic action.

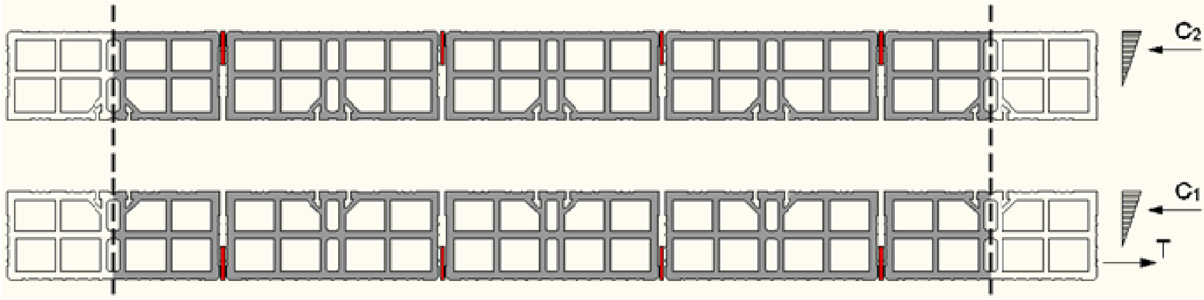

Figure 7. Reference section of system "PlastiBloc" with length of 1m. In red, between vertical joints of the hollow tiles, are inserted the strips.

The calculation of the stifness is executed by connecting the behavior of the structural element in a mechanical model equivalent to a beam supported on the ends. The no tension model assumed for the masonry and the presence of the reinforcement with the strips makes it so that the contribution to the stifness of the wall is reduced to only one of the face.

Numerical model was made with the finite element non linear software.
In the modeling of the PlastBloc system components, the following hypothesis were adopted:

- The cross section of the wall does not remain plain;
- The brick blocks are assumed rigid. The final element used is of thick-shell type;
  The plastic joints do not offer traction resistance, it is assumed that the contact between them and the blocks happens therefore punctually;
- The external constraints are of the hinge type;
- The strips give a contribution to the resistance for traction only.

The tests are conducted in non-linear range. The sources of non-linearity are:

- the material.
  In fact, the strips only resist to compression and therefore their contribution should not be considered in the event that such a state of strain establishes itself;
- geometric.
  The geometry of the model changes significantly during the analysis, due to the reduced stiffness respect to the horizontal actions; deformations are therefore of significant amplitude and the second-order effects may not be negligible.

COMPARISON OF RESULTS

The obtained results are compared with respect to six parameters:

1st mode — is natural period of vibration of the wall
C_1 — is the compression force in the external face of the wall
C_2 — is the compression force in the internal face of the wall
T — is the traction in the strips
d — is the displacement under sesmic demand

Table 1. Comparison between the results of simplified and FEM model.

Model	1st mode (sec)	C_1 (kN)	C_2 (kN)	T (kN)	d (mm)
Analytical	0.29	15.4	15.4	12.1	6.0
FEM	0.31	13.6	12.4	11.9	15.0

PLASTIBLOC VS TRADITIONAL SOLUTION

The difference between innovative system PlastiBloc and traditional one with common poroton bricks is remarkable.

The traditional masonry wall can't offer an effective response against the seismic forces, unless changing the structural configuration and consequently masses, stifness, dynamic behavior, increasing to much the final cost.

Others factors influence the global judgment and increase the gap between them, as shown in previous paragraphs. However the principal remain the seismic behavior.

DESIGN GUIDELINES FOR THE EVALUATION OF CAPACITY OF IN-PLANE AND OUT-OF-PLANE OF INFILL PANELS

Current code does not provide the in-plan verification of the infills, for actions to SLS or CLS, but only for those to the DLS (Italian Code NTC-08, 2008). The safety level of buildings cannot be expression of the capacity to the only structural elements, like saying that the vulnerability is concentrated exclusively in they. Something previously said, reflect about the incidence of the number of victims caused from the collapse of infills, compared to the total.

The structural safety must be instead evaluated checking all the sources of vulnerabilities of the building, intending thereby those elements that can represent a risk for the human life.

In the light of the role that the prevention of the collapse of the non structural elements assume in the safety of the buildings, existing or new, it is to be hoped that the future codes comprise the verifications to ULS of the infills to those already provided.

Therefore, in addition of the verifications to the DLS, the instructions are extended also to the SLS.

The limit displacement in the Life Safety Limite State (SLS), even if not required from the NTC-08, but desirable if it is wanted to be conferred to the buiding an adeguate safety level, can be set a factor of behavior, in relation to the structural tipology. Assuming, for example, $q = 4$, we obtaine:

$d_r \leq 0{,}04\ h$

With a height of 5 m and assuming, as observed in the experimental tests, than the sliding it is evenly distribuited on the height of the infill panel on the 5 beds of joints (Fig. 7), we obtain that the limitations are respective to 3 and 12 milimeter. Both values are widely lower to the displacement limit determined experimentally and proposed as upper bound, respectively 10 mm and 20 mm (Vailati et al., 2014).

CONCLUSION

A innovative solution for the realization of seismic-resistance infill panels has been presented. It is distingueshed to introduce of termo-formed joints made by recycled plastic, instead of mortar joint. Recent studies (Vailati & to 2014) have highlighted the potentialities of the technology applied to the control of the damage of infill walls, produce by in-plane and out-of-plane forces.

The evolution of the joint to the constructive system PlastiBloc, has allowed to integrate in the same technology a range of performance requirements that the conventional solutions can supply only with additional technologies.

Studies on walls of sizeable height, where the accelerations have medium intensity, shown that also in extreme design conditions, the proposed technology it be able to supply an adequate level of safety.

Simplified models for the design/verify of the infills allow to estimate in simple and effective way the behavior of the wall, giving the outcomes near close to those obtained with more advanced non linear models.

The possibility to modify some design factors, for example the strengthening with strips or tickness of internal insulating layer, makes the system easily adaptable to every design situation.

In the high seismic hazard areas, the proposed technology proves very effectiveness, since concurs to avoid the use of strengthening techniques against the expulsion of bricks.

The guidelines shown at the end of work, gives to practioner an operating tool to check the performances of non structural elements under seismic loads.

REFERENCES

Abrams DP, Angel R, Uzarski J (1996) "Out of plane Strength of Unreinforced Masonry Infill Panels", *Eartquake Spectra*, 12 (4): 825-844

Brokken S, Bertero VV (1981) "Studies on effects of infills in seismic resistant RC construction", *Report UCB/EERC*, 81-12 University of California, Berkeley

Circolare n. 617 C.S.LL.PP. (2009) "Istruzioni per l'applicazione delle nuove norme tecniche per le costruzioni di cui al decreto ministeriale 14 gennaio 2008", *Supplemento ordinario n. 27 alla Gazzetta Ufficiale 26 febbraio 2009*

D.Lgs. 311 (2006) "Disposizioni correttive ed integrative al decreto legislativo 19 agosto 2005, n. 192, recante attuazione della direttiva 2002/91/CE, relativa al rendimento energetico nell'edilizia", *Gazzetta Ufficiale della Repubblica Italiana 1 febbraio 2007*

DM 14 Gennaio 2008 "Nuove norme tecniche per le costruzioni", *Gazzetta Ufficiale della Repubblica Italiana 4 febbraio 2008*

Fardis MN, Panagiotakos TB (1998) "Seismic response and design of masonry infilled reinforced concrete buildings", *Structural Engineering World Congress*, San Francisco

ISO/TS 14067 (2013) "Greenhouse gases. Carbon footprint of products. Requirements and guidelines for quantification and communication".

Kaufmann E (1955) An American Architecture, Horizon press, E. Kaufmann, New York.

UNI EN ISO 13786 (2008) "Thermal performance of building components. Dynamic thermal characteristics. Calculation method".

Vailati M, Caluisi A, Monti G (2014) "Environmentally-friendly joints for seismic resistant infill panels", *atti delle giornate AICAP 2014-Strutture nel tessuto urbano,* 22-24 maggio, Bergamo.

Vailati M (2004) Contenuti dell'ordinanza n.3274 in materia di costruzioni antisismiche, risvolti applicativi e confronti con altre normative, 2nd Level Master Degree Thesis, 3rd University of Rome,Italy.